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Results of the MAJORANA DEMONSTRATOR's Search for Double-Beta Decay of ^{76}Ge to Excited States of ^{76}Se

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Abstract. The MAJORANA DEMONSTRATOR is searching for double-beta decay of ^{76}Ge to excited states (E.S.) in ^{76}Se using a modular array of high purity Germanium detectors. ^{76}Ge can decay into three E.S.s of ^{76}Se . The E.S. decays have a clear event signature consisting of a $\beta\beta$ -decay with the prompt emission of one or two γ -rays, resulting in with high probability in a multi-site event. The granularity of the DEMONSTRATOR detector array enables powerful discrimination of this event signature from backgrounds. Using 21.3 kg-y of isotopic exposure, the DEMONSTRATOR has set world leading limits for each E.S. decay, with 90% CL lower half-life limits in the range of $(0.56 - 2.1) \cdot 10^{24}$ y. In particular, for the 2ν transition to the first 0^+ E.S. of ^{76}Se , a lower half-life limit of $0.68 \cdot 10^{24}$ at 90% CL was achieved.

1. Introduction

Double-beta ($\beta\beta$) decay is the subject of a varied experimental program. Of particular interest is neutrinoless double-beta decay ($0\nu\beta\beta$), a hypothetical lepton number violating process that would indicate that the neutrino is a Majorana fermion. While two-neutrino double-beta ($2\nu\beta\beta$) decay has been directly observed in eleven isotopes, $0\nu\beta\beta$ has not yet been observed. Most $\beta\beta$ isotopes have multiple daughter excited states (E.S.) that they can decay into; for example, the decay scheme of ^{76}Ge is shown in Figure 1. Such decays will have a reduced Q-value, with the remaining decay energy emitted as one or more γ s. These γ s will typically travel a few centimeters before interacting in bulk material, resulting in multiple energy deposition sites.

Measurement of the half-life of $2\nu\beta\beta$ to E.S. provides a useful check on the accuracy of $2\nu\beta\beta$ nuclear matrix element calculations; in turn, this may help evaluate the $0\nu\beta\beta$ matrix elements. In addition, $\beta\beta$ decays to E.S. are sensitive to physics beyond the standard model. The half-life of $0\nu\beta\beta$ decay to E.S. is sensitive to the underlying physics mechanism [1]. The half-life of $2\nu\beta\beta$ decay to 2^+ E.S. is sensitive to a hypothetical bosonic component to neutrinos [2, 3]. So far, $2\nu\beta\beta$ to the first 0^+ daughter E.S. has been observed in ^{100}Mo and ^{150}Nd , with a tension between these observations and theoretical half-life estimates [4].

2. The MAJORANA DEMONSTRATOR

The MAJORANA DEMONSTRATOR [5] is searching for $0\nu\beta\beta$ of ^{76}Ge using HPGe detectors. The experiment consists of two separate modules, consisting of arrays of detectors operated in separate cryostats in vacuum. 44.1 kg of detectors are used, 29.7 kg of which are enriched to 88% in ^{76}Ge , allowing them to act as both the source and detector of $0\nu\beta\beta$. The detectors in each module are shown in Figure 2. In order to minimize backgrounds, the experiment is constructed using ultra-low background materials and is placed within a multi-layered shield shown in Figure 3.

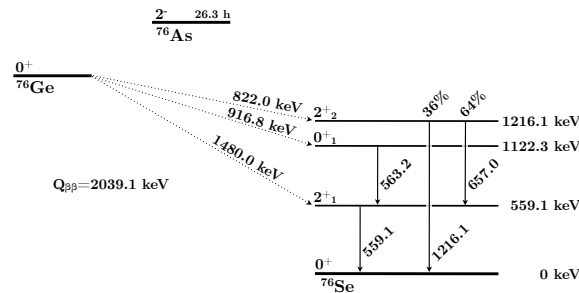


Figure 1. Level diagram of the $\beta\beta$ -decay of ^{76}Ge into ^{76}Se .



Figure 2. A drawing of the content of module 1 (top) and 2 (bottom). Blue detectors have the natural ^{76}Ge isotopic abundance, while green are enriched to 88%.

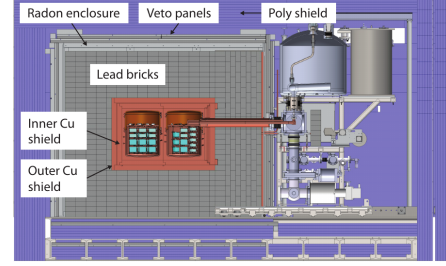


Figure 3. A drawing of the MAJORANA DEMONSTRATOR shield, with modules inserted.

The experiment is housed at the 4850' level (4300 m.w.e) of the Sanford Underground Research Facility (SURF) in order to minimize exposure to cosmic ray muons; in addition, scintillating polyethylene veto panels surround the experiment and actively veto additional muons. The HPGe detectors use the P-type Point Contact (PPC) detector geometry, which has advantages in energy resolution. The PPC geometry and the granularity of the detector array enable discrimination of single- and multi-site events.

The MAJORANA DEMONSTRATOR is also searching for $\beta\beta$ decay to excited states in ^{76}Ge , which has not yet been observed in this isotope. ^{76}Se has three E.S. that ^{76}Ge can decay into, as shown in Figure 1. $2\nu\beta\beta$ to the 0_1^+ state has the shortest expected half-life, with theoretical estimates ranging from $1.0 \cdot 10^{23} - 7.1 \cdot 10^{24}$ y [4]; since the DEMONSTRATOR has a sensitivity within this range of half-lives, this state will be the focus of this document. The 0_1^+ E.S. decay mode has a Q-value of 917 keV and two γ s, with energies 559 keV and 563 keV. Because $\beta\beta$ to E.S. is an inherently multi-site event, the DEMONSTRATOR can significantly reduce its backgrounds by searching only for events that involve multiple detector hits. In particular, we will search for peaks at 559 keV and 563 keV in individual detectors within multi-detector events. Multi-detector events are built to include all detector hits within a $4 \mu\text{s}$ rolling window; this is a conservative window that is expected to capture all truly simultaneous detector hits.

3. Background Cuts and Detection Efficiency

This analysis uses the standard channel selection, data cleaning, and muon cuts developed for the MAJORANA DEMONSTRATOR's $0\nu\beta\beta$ analysis [5]. In addition, the detector hits in coincidence with candidate gamma hits will provide additional observables that can be used to further cut backgrounds. Since 95% of ^{76}Ge is contained in enriched detectors and the $\beta\beta$ site will be contained in a separate detector from the gamma peak, events in which none of the coincident detectors are enriched are cut.

The largest source of backgrounds for this analysis is γ rays, which are often multi-site events. Because background γ s will mostly originate from a handful of known isotopes, they can be cut based on the energies of coincident detector hits. Multi-detector events caused by γ cascades will commonly produce coincidence hits with known energies. Compton scattered γ s will commonly produce multi-detector events where the sum of energies between detectors has a known energy. For this reason, the sensitivity of the analysis can be improved by selecting a set of energy ranges for coincident detectors and for the sum of all detectors to cut. The energy windows are algorithmically selected in order to optimize the detection sensitivity based on simulations of the backgrounds and each E.S. decay mode. Figure 4 shows the energy ranges selected for the first 0^+ ^{76}Se E.S. The expected effect of these energy cuts is to improve the signal to background ratio by a factor of 3.9 for the 559 and 563 keV γ peaks.

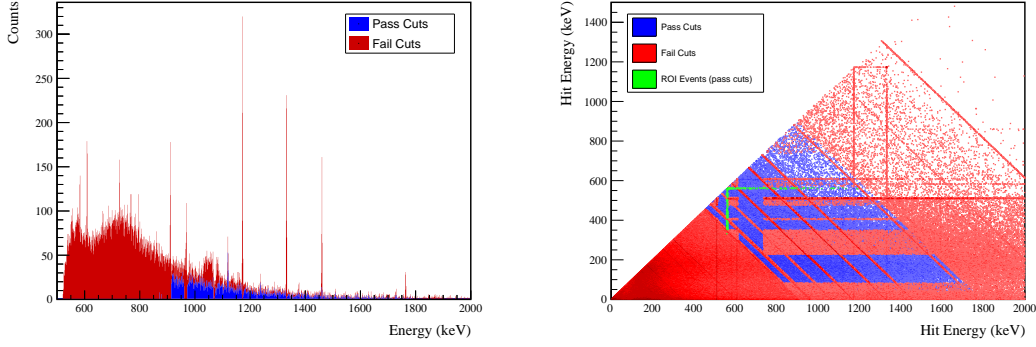


Figure 4. Effect of sum and coincident energy cuts on a simulated background model. Left: Sum energy spectrum of multi-detector events. Right: energy spectrum of multiplicity 2 events.

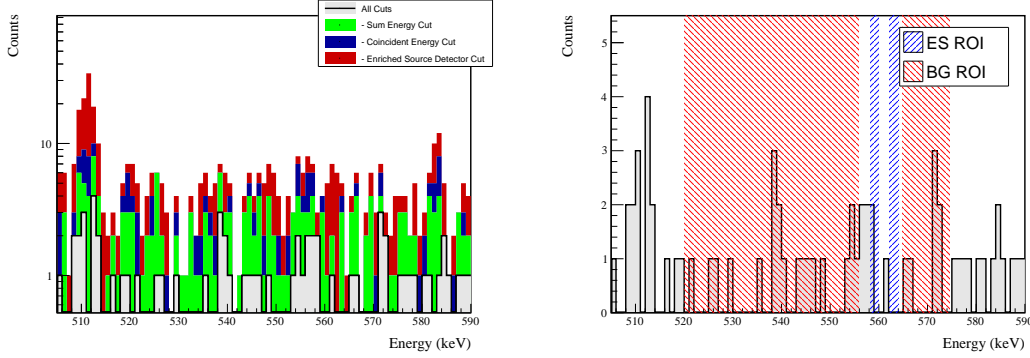


Figure 5. Measured background spectrum with each cut sequentially applied (left), and background and signal ROIs labelled (right).

MAGE [6], a GEANT4 [7] based simulation package containing a simulated geometry of the MAJORANA DEMONSTRATOR, combined with the DECAY0 [8] $\beta\beta$ -decay event generator, were used to produce simulations of each E.S. decay mode for ^{76}Ge . Using these simulations, the detection efficiency for the first 0^+ ^{76}Se E.S. decay mode was estimated to be $2.3 \pm 0.2\%$ for module 1 and $1.0 \pm 0.2\%$ for module 2.

To test the accuracy of the simulated detection efficiencies, pair production events produced by a ^{56}Co calibration source acted as a proxy for the $\beta\beta$ E.S. events. Multi-detector events with a 511 keV annihilation γ detected in coincidence with single- and double-escape peak (SEP and DEP) events are used to immitate the detection signature; single-detector events in the SEP and DEP are used to control for the total rate of these events in order to estimate a detection efficiency. The detection efficiency is measured from ^{56}Co calibration data and simulations in 16 different SEP and DEPs. The differences are used to estimate the systematic error associated with the simulated detection efficiencies. The dominant systematic uncertainties originate from the detector dead layer thickness and inaccuracies in the simulation.

4. Results

A 90% confidence limit was set for each E.S. decay mode using frequentist techniques. Open data recorded in both modules between January 12, 2016 and April 18, 2018 were used for this analysis, with a total isotopic exposure of 21.3 kg-y. A Poisson peak counting analysis was

performed; for the first 0^+ E.S., the combined regions of interest, consisting of a 1.6 keV range around the 559 and 563 keV γ peaks, 2 counts were measured, with 2.02 background counts expected. Figure 5 shows multi-site hits after all cuts around these ROIs. For each decay mode, a world leading limit was set, as shown in Table 1.

Table 1. Table of limits at 90% CL for each $\beta\beta$ to E.S. decay mode

Decay Mode	Q-value	γ Energies	Previous Limit	MJD Limit
$0_{g.s.}^+ \xrightarrow{2\nu\beta\beta} 0_1^+$	916.8 keV	559.1+563.2 keV	$3.7 \cdot 10^{23}$ y [9]	$6.8 \cdot 10^{23}$ y
$0_{g.s.}^+ \xrightarrow{2\nu\beta\beta} 2_1^+$	1480.0 keV	559.1 keV	$1.6 \cdot 10^{23}$ y [9]	$9.6 \cdot 10^{23}$ y
$0_{g.s.}^+ \xrightarrow{2\nu\beta\beta} 2_2^+$	822.0 keV	559.1+657.0 keV or 1216.1 keV	$2.3 \cdot 10^{23}$ y [9]	$5.6 \cdot 10^{23}$ y
$0_{g.s.}^+ \xrightarrow{0\nu\beta\beta} 0_1^+$	916.8 keV	559.1+563.2 keV	$1.3 \cdot 10^{22}$ y [10]	$2.1 \cdot 10^{24}$ y
$0_{g.s.}^+ \xrightarrow{0\nu\beta\beta} 2_1^+$	1480.0 keV	559.1 keV	$1.3 \cdot 10^{23}$ y [11]	$1.1 \cdot 10^{24}$ y
$0_{g.s.}^+ \xrightarrow{0\nu\beta\beta} 2_2^+$	822.0 keV	559.1+657.0 keV or 1216.1 keV	$1.4 \cdot 10^{21}$ y [12]	$1.6 \cdot 10^{24}$ y

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